HAND LAY-UP OF COMPLEX GEOMETRIES – PREDICTION, CAPTURE AND FEEDBACK

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ABSTRACT

This paper presents a process improvement framework built on previous research activities at the University of Bristol. The work focusses on hand lay-up and seeks to reduce variability, improve productivity and increase manufacturability of future designs. The framework is based on a double-loop learning model which incorporates prediction, capture and feedback. The predictive method employed uses a kinematic drape model as part of an expert system. The expert is needed to translate the model outputs into a more realistic set of drape instructions. The lay-up is captured by video analysis and quality data captured using an on-line tool. This data is then fed back to the user to facilitate decision making.

1. INTRODUCTION

Composite materials, such as carbon-fibre reinforced plastics (CFRP), have seen increased adoption levels in many industrial sectors, particularly transport, aviation, wind and marine power, and industrial applications. The principle reasons being beneficial properties in terms of specific strength and stiffness, as well as environmental properties such as corrosion resistance. For the transport and aviation sectors, future emissions regulations [1, 2] mean reductions in the dry vehicle mass will likely necessitate the use of composite materials. In the automotive sector, for example, historical composites use was restricted to higher-end vehicles which had relatively small production volumes and rates [3]. However, composite materials have seen use in more mainstream vehicles, with the BMW i3 city car being a notable example. By comparison the BMW i3 was expected to be produced at a rate of around 30,000 vehicles per annum, compared with 3,000 for the McLaren MP4-12C [3, 4]. Higher production volumes are likely to become the norm as manufacturers strive to meet future emissions targets.

The barriers to achieving these higher production rates are cost and productivity, with raw material supply being another issue which will not be discussed here. Cost can be separated into material cost and processing cost. Material cost will not be investigated as part of this work, but processing cost, which comprises around 40 % of the total part cost [5], includes labour and quality-associated costs. Reducing these costs and improving productivity in composites manufacturing form the primary motivation for this work.

1.1 Hand Lay-up

There are a wide variety of viable options for manufacturing a CFRP component. Amongst these the placement of plies onto a mould tool by manual labour is responsible for up to 75 % of manufacture [6]. Hand lay-up is one of the oldest methods of composite fabrication and still remains a relevant process, in spite of the current industry drive toward automation. There are a number of reasons for this, which will be discussed below, but an in-depth comparison of manual and automated composites fabrication methods is beyond the scope of this paper.

One of the main reasons for preferring human operators over automated processes is flexibility. This flexibility has two sources: flexibility of task and flexibility of geometry and material. Flexibility of task can simply be understood as the person being effectively re-purposed, or being capable of multiple tasks, from lay-up to vacuum bagging or tool preparation, whilst most automated solutions are solely focussed on material deposition, such as Automated Fibre Placement (AFP). This means that for a given recurring cost a manufacturer has a flexible production unit, versus a larger initial outlay for a single-purpose production unit, albeit one with lower recurring costs.

The second type of flexibility is the range of possible geometries, and materials, which can be manufactured my human operators compared to many mature automated solutions. An example of this is pultrusion which is a highly automated process that is ideal for large volumes of parts with continuous cross sections [7]. However, it is limited to parts of continuous cross sections, which limits its application as a fabrication technique. The same can be said as a limitation of other automated material deposition techniques. Filament winding requires the material to follow a geodesic path [8]. Other techniques such as AFP and Automated Tape Laying (ATL) have greater geometric flexibility, although they are limited by the physical constraints of the end effector [9-12] and require extensive path programming for each new geometry to be manufactured. A human operator is capable of working with multiple materials and geometries and also has the advantage of gaining experience, thus reducing the “re-programming” time for each subsequent geometry.

Another important, and often overlooked aspect in the human operator versus automation debate, is the shop-floor footprint of a human operator compared to an AFP machine. When comparing relative productivities material deposition rate in kg/hr (or lbs/hr) is commonly used. This metric is too simplistic to reflect the rate which can be realistically achieved [13] and it also only compares production rate between a single AFP machine and a single operator. AFP has achieved lay-up rates of ~8.6 kg/hr [14] compared to ~1 kg/hr for manual lay-up [15]. However, for a relatively small component it is possible that for a given floor space, there could be room for as many as 9 lay-up stations in the space which 1 AFP machine takes up, including clearances. It is also possible that in a given manufacturing environment there also may not be enough vertical clearance for a standard AFP robot.

With all this in mind however, it is still felt that automated manufacturing methods will improve over time, particularly by cost reduction compared to labour costs. However it is unlikely that automation will ever completely replace operators, considering that for automated fibre placement the machine deposition time accounts for only 1/3 of the total cycle time [16, 17]. Additionally there will be parts which cannot be manufactured due to tight or complex geometries or production runs and part sizes for which automated manufacturing is not cost effective [15]. On a typical commercial airliner wing the ratio of manually laid-up parts to automatically laid-up parts is currently around 5:1 [18]. As a result of reducing the cost of the automatically manufacturing parts, the manually laid-up parts will make up an increasing proportion of the cost for a typical wing-set.

Because of these factors it is felt that hand (or manual) lay-up of composite parts is a useful area for investigation. By improving the level of control and standardisation between operators in the manual lay-up scenario the cost can be reduced, productivity increased and part-to-part variability minimised.

1.2 Complex Geometry

The complexity of a part's geometry is one of the key factors in opting to use manual lay-up techniques over automated methods. Complexity in this case means that the ply requires some on-tool work to ensure it conforms to the surface, essentially the ply requires some draping. Draping is the act of modifying a ply's as-cut geometry to match the contours of the tool surface. There are several mechanisms by which drape can be achieved [19, 20], and for a given geometry there are a number of possible starting points and sequences which can be used to achieve drape.

There are no fixed rules for what makes a particular part 'complex' or 'simple', but complex parts generally have double curvature (curvature in more than one direction), intersecting planes and sharp corners. What makes one feature more complex than another is in its severity. For example in [21] the complexity of the feature was defined as the ramp angle of the corner (shown in Figure 1) which gave a resulting increase in the time taken to lay-up. In most cases the complexity is reflected in the amount of shear required to form a part. An example of this is the increase in shear required to form a flat panel (no shear) to a hemisphere, which requires high amounts of shear or possibly even relief darts [8], although [19] demonstrates that by adjusting the starting point these may not be necessary.

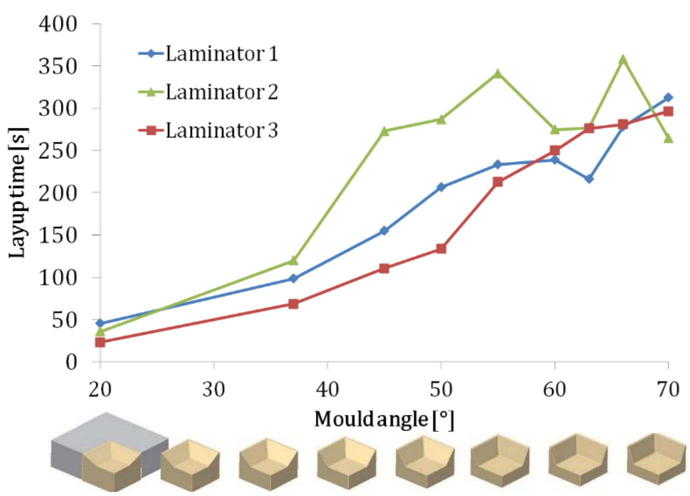


Figure 1: Variation of lay-up time with increasing feature severity [21]

For the purposes of this work a geometry was chosen based on an aircraft trailing edge panel (Figure 2). The features that make this geometry complex are the ramped corners and the central cut-out. There are a number of possible, intuitive drape routes which can be used to manufacture

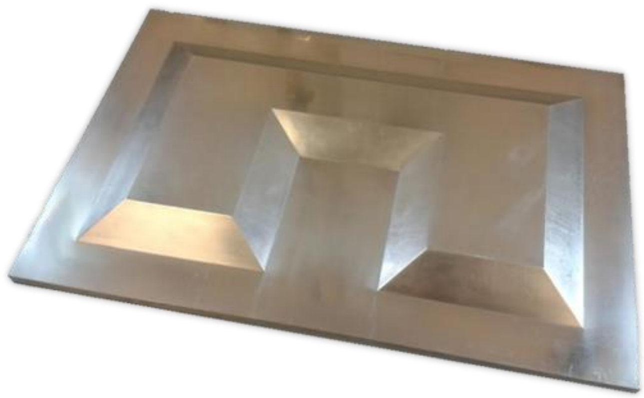


Figure 2: U-shaped ramped tool

the part which will give differing fibre orientation fields.

2. FRAMEWORK FOR IMPROVEMENT OF HAND LAY-UP

In order to improve manual lay-up there are some features of it which must be addressed. There are a number of sources which state that manual lay-up is inherently variable [8], [22]. Whilst there will be operator-to-operator variability, such as described by [21], the process itself is not necessarily variable as it is uncontrolled. A typical manufacturing instruction sheet (MIS) will only contain the stacking sequence of the plies and some other process information, such as debulk schedule. As [19, 20] show there is a sequence of events which are required to drape a ply, this sequence is typically not displayed to the operators. Additionally there is the subject of assistive tools. Reference [23] shows that each laminator has his or her own set of tools which are personal to them. As such they are themselves an additional source of variability. Reference [23] goes on to capture how these tools are used and proposes a standardised tool for assisting lay-up, thus removing the variability between tools.

Aside from variability there is also a lack of feedback from the shop floor into the design phases of a project [24]. This lack of feedback between manufacturing phases mean that composites design and manufacture more closely resembles a waterfall process. In a waterfall process knowledge only travels downstream, in this case from designers to engineers to laminators. However it is accepted that there is some degree of skill required to carry out hand lay-up [15, 21. 24-26], so it would be beneficial to introduce some feedback mechanism from the shop floor back into the early design phase.

The waterfall process also only allows for single-loop learning (Plan, Do, Check, Act; or PDCA) within a production process, meaning that any new learning gathered is not transferred into other projects as would be the case with a more agile, double-loop system. The purpose of this work was to create a framework in which data could be captured, organised and presented in order to facilitate these learning objectives. At the same time, the use of a framework in this manner

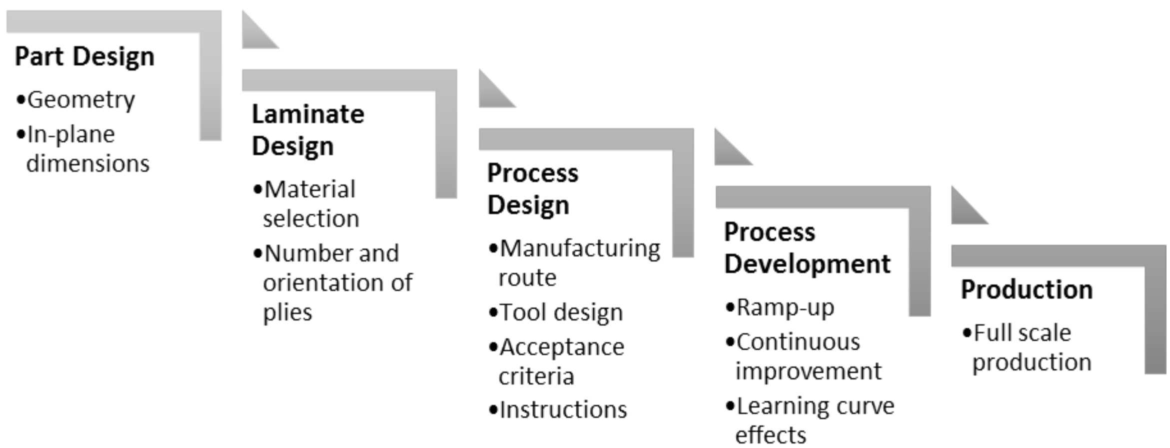


Figure 3: Waterfall process for design and manufacture of composite components

would give rise to greater standardisation of the manual lay-up process.

2.1 Methodology

The purpose of this paper is to demonstrate the framework created at the University of Bristol to improve hand lay-up. First to be discussed are some of the predictive capabilities for hand lay-up, followed by how the lay-up activity itself can be captured and codified and lastly how this data and other captured information can be organised and fed-back both to operators and designers. The initial system was taken as a Deming Cycle [27] modified for manual lay-up (Figure 4). Then some control loops were added in order to reduce the variability mentioned previously. Lastly a secondary feedback loop was added to change the system from a single-loop system to a double-loop system, as proposed in reference [28]. With this initial framework in place, methods for the individual loops could then be investigated. These activities fell into three categories: Predict, Capture and Feedback. These activities and their associated methods and results will be discussed in the following sections.

3. PREDICTION

In order to improve standardisation and properly assess productivity some predictive capacity is necessary. The predictive methods developed within this framework relate to the drape route, potential productivity and defect prediction. Within the PDCA cycle prediction covers aspects of ‘Plan’ as it can be used to generate instruction sets and process plans and, the defect prediction especially, the ‘Check’ phase, as shown in Figure 4.

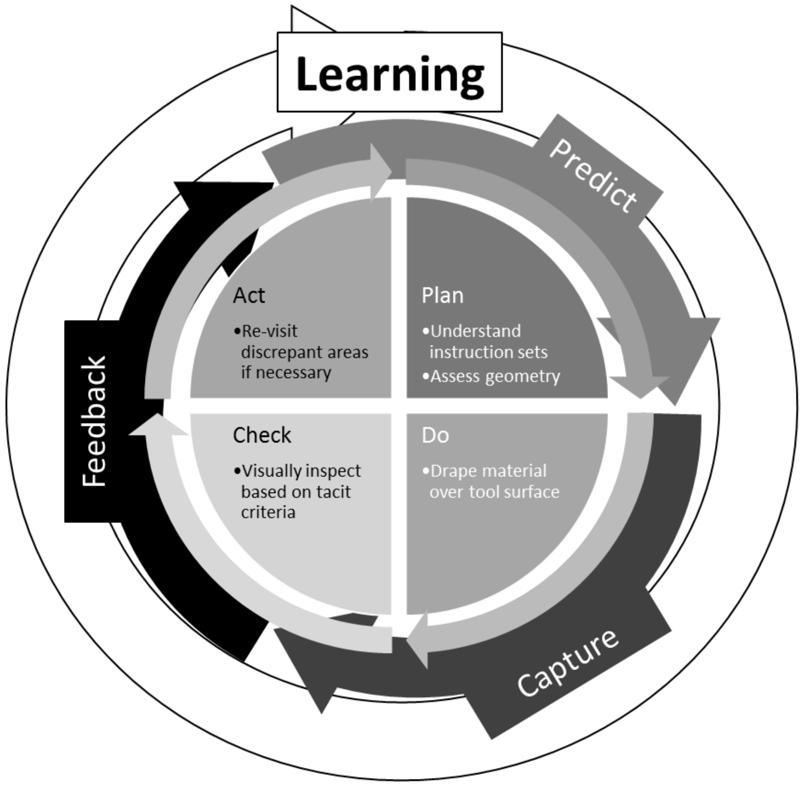


Figure 4: Framework for improvement of manual lay-up. Comprises of a PDCA cycle nested within a Predict, Capture and Feedback loop, which is in turn nested within a learning loop

3.1 Drape Prediction

There are a number of commercial codes and algorithms which can be used for drape modelling. These broadly fall into two categories: finite element based models and kinematic models. For the purposes of integrating a predictive model into a cyclical framework a kinematic model was preferred as finite elements models, though very precise and detailed, have much longer run-times. Kinematic drape models are based on fixing 3 nodes of a pin jointed net and rotating the fourth node until it meets the surface geometry. As such they are typically used for modelling woven materials as they mimic the fabric unit cell, although preliminary work at the University of Bristol shows they provide reasonable estimates of unidirectional materials as well.

The particular drape model selected for use in this framework was one that had been developed as a result of the work presented previously [19, 20], called Virtual Fabric Placement (VFP). The advantage of this particular model over commercial options is that it works interactively, rather than selecting the highest point on the geometry and draping out from it. The importance of the interactivity in this scenario is that it allows designers and process engineers to quickly trial several different start points and drape paths and assess them visually. The outputs of this are the fibre orientation field, the 'stick paths' which the drape follows and the flat pattern needed to produce the ply.

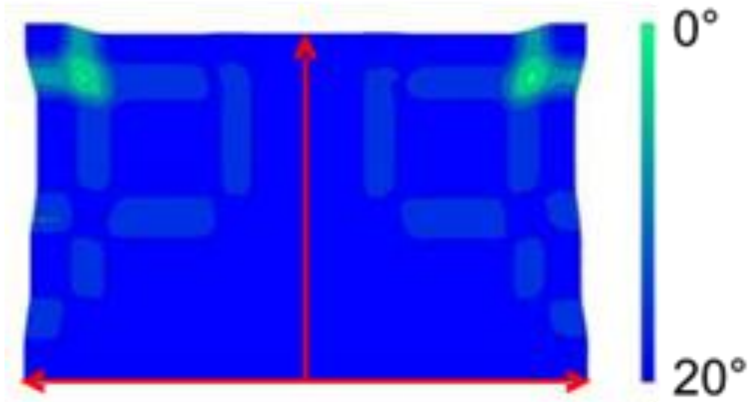


Figure 5: VFP output of tool shown in Figure 2. Arrows represent stuck path directions.

There is one principle issue of kinematic drape models, however. Since the output consists of orthogonal stick paths, and this is not a realistic reflection of the feature-by-feature approach used by composite laminators [25]. The predictive capacity is thus enhanced as in reference [25] by the use of an expert laminator, who is familiar with both the drape process and the drape prediction. The outputs of this process are more detailed instructions than achieved either currently or by the drape algorithm alone.

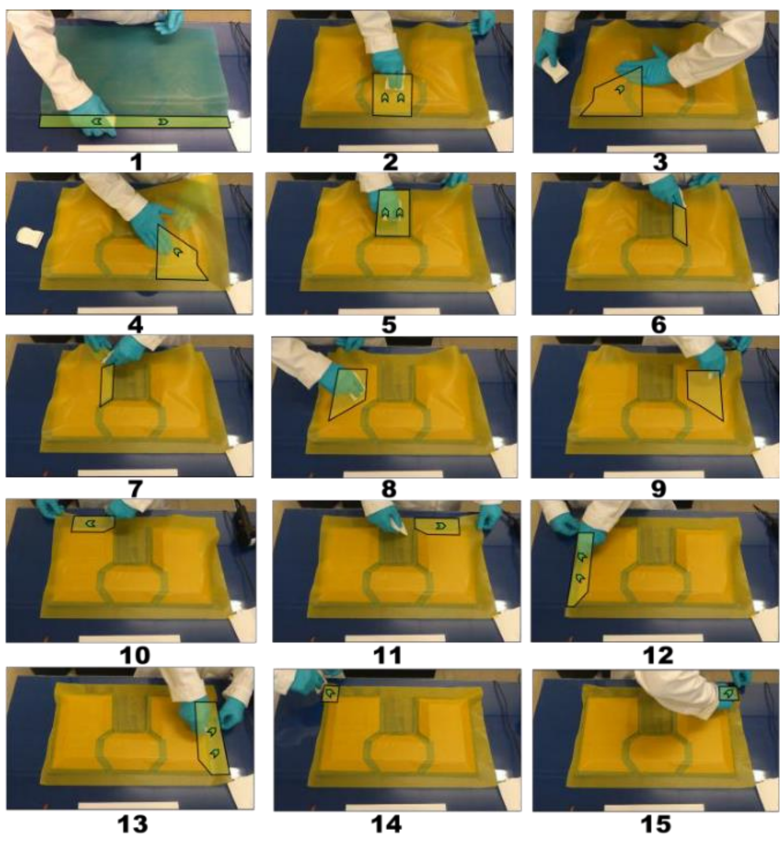


Figure 6: 15 step drape process developed by an expert laminator in conjunction with VFP [25]

3.2 Production Rate Prediction

Typically production rate is assumed as a kg/hr value, which, as has been mentioned previously, is not a suitable metric as there are many factors which affect the actual productive rate. As a result of this the framework employs two additional productivity models, one based on material data [29] and one based on geometry and shear energy outputs from VFP [30]. These two values for the expected time taken, much like the VFP output do not currently give accurate timings for lay-up, but do give an indication of the time taken when selecting materials or selecting a drape sequence. Much like the VFP outputs, the use of an expert to 'sanity check' these predictions against experience will be necessary for them to be useful.

3.3 Defect Prediction

The last predictive model to be integrated into this framework is one which is intended to highlight potentially defective areas. For this predictive model there is an emphasis placed on bridging and wrinkling. Of particular interest is in the code's ability to predict secondary bridging, a form of bridging which occurs when stuck material is lifted from the tool by subsequent drape operations.

Wrinkling is likely to occur in areas of high excess shear, predicted by VFP in the corners of the part. This predictive code is able to identify areas of high shear and its direction and display this data visually to user (Figure 7).

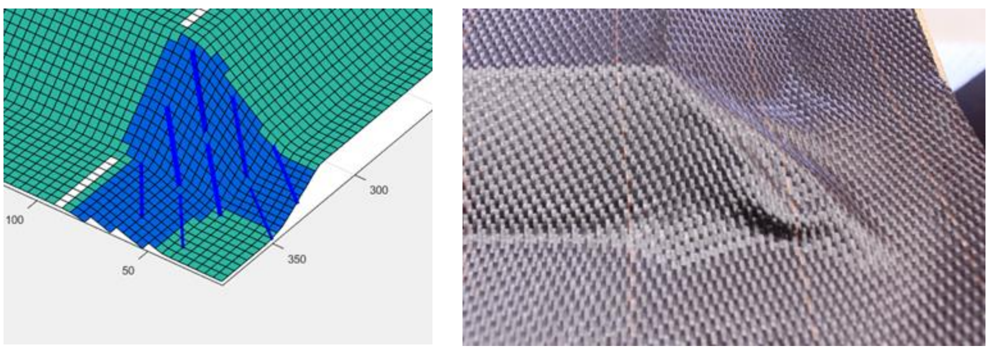


Figure 7: Prediction of area of excess shear and corresponding observed defect

Bridging and secondary bridging is caused by tension in an area of material deficit which causes the ply to lift away from the surface. This creates a pocket of resin, or in the worst case, air which is detrimental to the structural integrity of the part. The amount of material deficit is determined by the location of the ply's point of contact with the tool to the ply free edge. This code is able to determine areas of likely material deficit and using the shear data generated by VFP, determines the forces in that area. If tension is present there is a risk of bridging. Figure 8 shows the positions on the part which are most at risk of bridging, the larger the marker, the higher the risk.

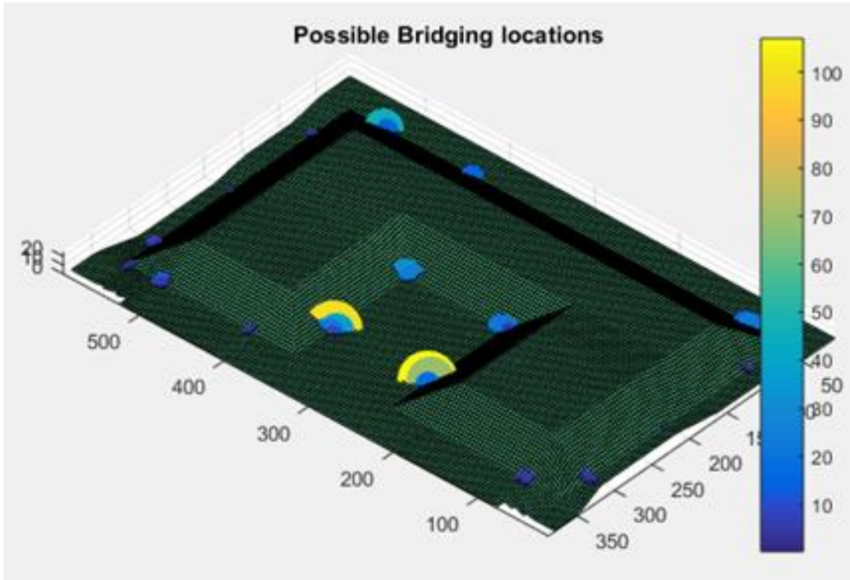


Figure 8: Risk map of bridging, larger indicators show higher risk of bridging at that location

4. CAPTURE

In order to improve quality and the accuracy of the predictive models, data on the specifics of the lay-up process must be collected. The importance of data capture lies in extracting tacit knowledge from the shop floor. Since the manual lay-up process is effectively uncontrolled, it can be treated as a craft process, where the laminator effectively 'completes' or realises the design intent. The specifics of how this is achieved are really only known to the laminators. Therefore it would be instructive to learn from their gathered experience in order to improve component design for hand lay-up.

Capture of shop-floor level data could also be used as an additional conformance or quality metric. There is also the potential for assessment of the task ergonomics such as posture and gaze detection, although this has not been studied as part of this work. The capture activities consisted of video analysis of the drape process and quality data capture.

4.1 Video Analysis

Laminators were observed laying up the component shown in Figure 2 and their hands were analysed to give a time and motion study of hand position relative to the tool co-ordinates. A MATLAB code was used to analyse the videos and determine the position of the laminator's hands within the frame. The positions were then identified for the left and right hands and plotted over the image of the tool to show where the manipulations occur on the ply.

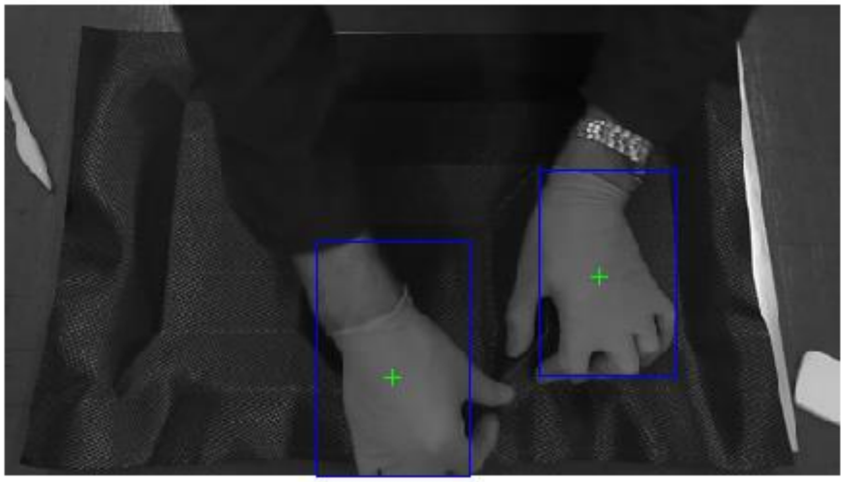
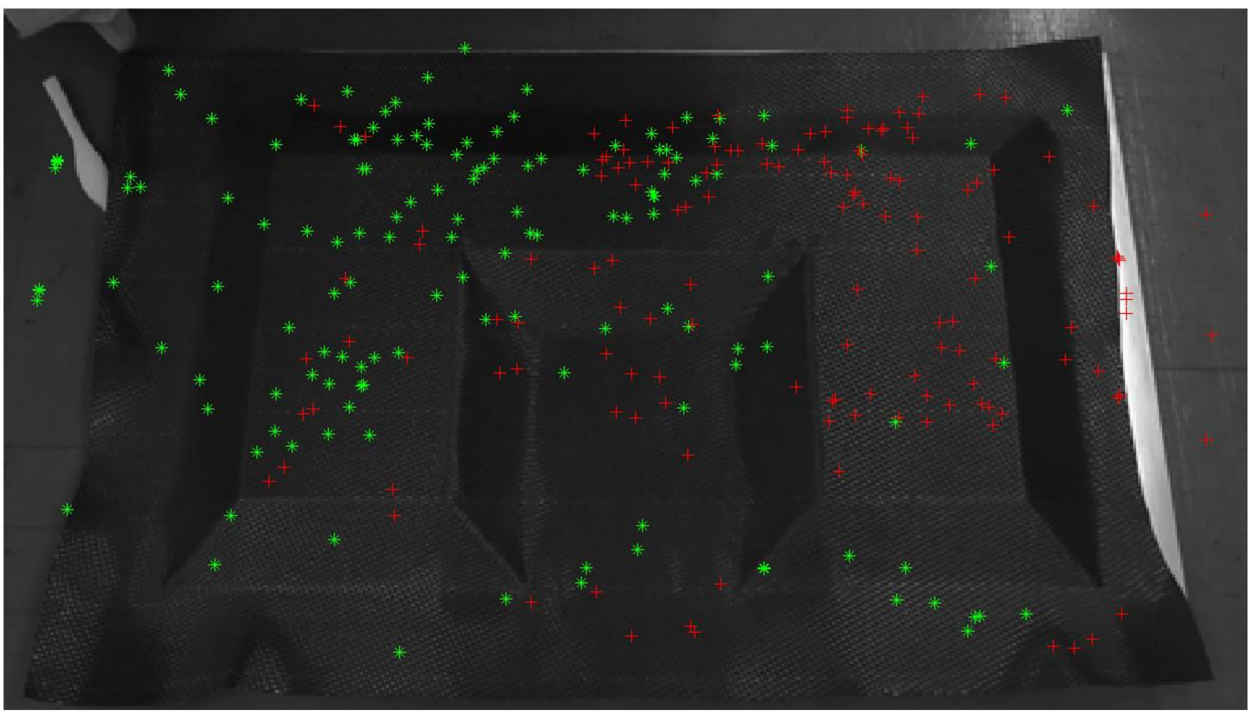


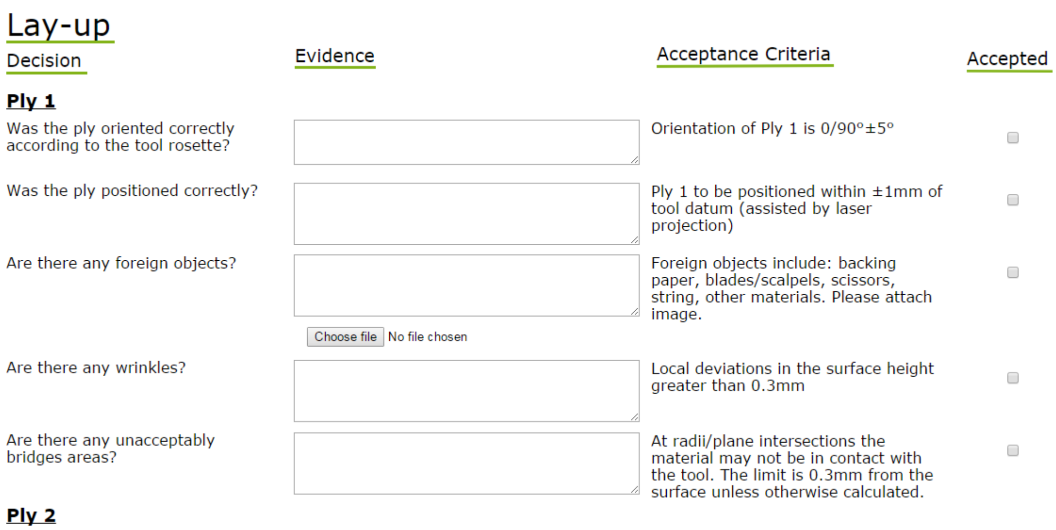
Figure 9: Example of hands being tracked by video analysis code



The points illustrate that for the most part, the lay-up is symmetrical although the cluster in the lower right-hand corner (highlighted on the figure) shows that there is some continued activity in this corner. This agrees with the prediction of high shear in this region. However the fact that it does not appear on the opposite corner shows that, unlike the VFP prediction the lay-up route is not symmetrical. By using this tracking method a comparison can be made between the instructions as-written and the more detailed manipulations required to drape the ply.

4.2 Quality Information Capture

In addition to the data captured by video analysis there is also a wealth of quality related information which can be captured from the shop floor. Most instruction sets will have a stamp or signature to indicate compliance, but will leave how compliance was achieved up to the laminator. There is the potential for different laminators to have different takes on the same quality requirement, due to some inconsistencies which are typically present [31]. By using an on-line quality data capture tool, as described in reference [31], this tacit information can be captured and used to prevent laminators re-solving the same issues over and over. This will allow for standardisation of re-work procedures and in-process fixes.



Lay-up

Decision	Evidence	Acceptance Criteria	Accepted
Ply 1			
Was the ply oriented correctly according to the tool rosette?		Orientation of Ply 1 is 0/90°±5°	
Was the ply positioned correctly?		Ply 1 to be positioned within ±1mm of tool datum (assisted by laser projection)	
Are there any foreign objects?	Choose file No file chosen	Foreign objects include: backing paper, blades/scalpels, scissors, string, other materials. Please attach image.	
Are there any wrinkles?		Local deviations in the surface height greater than 0.3mm	
Are there any unacceptably bridges areas?		At radii/plane intersections the material may not be in contact with the tool. The limit is 0.3mm from the surface unless otherwise calculated.	
Ply 2			

Figure 11: Example of the on-line quality data capture tool

The on-line quality data tool also has a defects submission portal. In this area users are invited to submit images and text descriptions of discrepancies which arise during manufacture. These can then be collated by part and by feature and used to inform design for manufacture decisions.

By using a persistent, on-line capture system in this way, a permanent and searchable record is created. This database can be used as part of the double-loop learning system to inform designers of the likely issues which can arise from particular geometric features, in addition to the information provided by simulation.

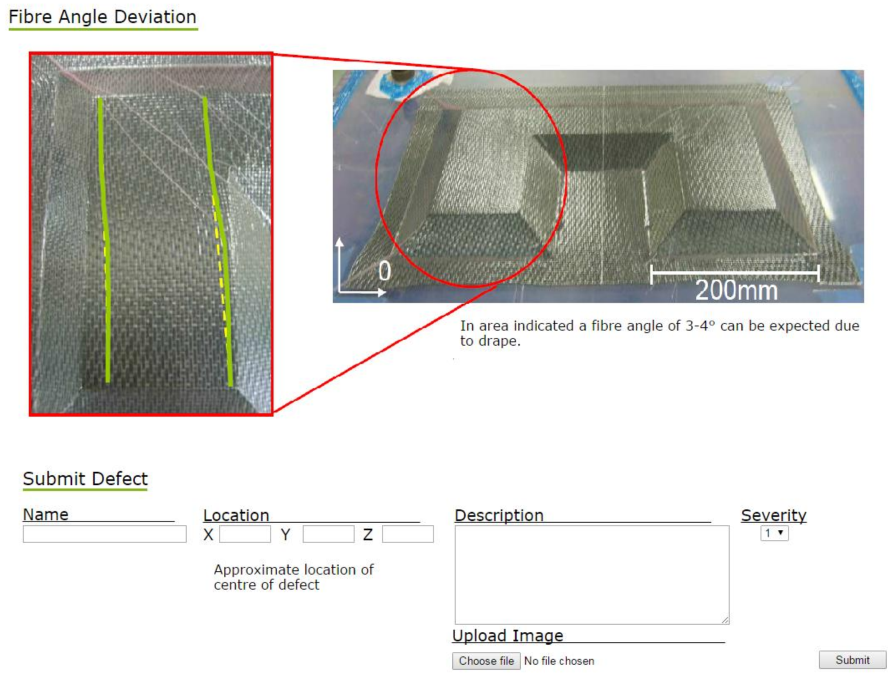


Figure 12: Example of defect recorded in the defect portal

5. FEEDBACK

All of the information gathered and generated during the prediction and capturing activities needs to be fed-back into the system in some way in order to give effective improvements in quality and productivity. The feedback occurs at two levels: single-loop and double-loop. The single-loop feedback is information presented at the point of use to the user, such as display of the modelling outputs or projected information displayed to the operator. This information is an important part of a PDCA cycle as it gives extra information, beyond experience to assist with the Check-Act potion of the cycle.

Where the feedback elements become more complex is in second, or learning, loop as the data needs to be converted to knowledge. This conversion process will be a more subtle point of change, but will result in fewer re-loops of the PDCA cycle in the future, ideally leading to all parts and projects being right first time. The learning will be facilitated by the organisation of the data, which will be arranged into a repository referred to as the knowledgebase. From here various features can be consulted by way of a look-up table initially until their use becomes second nature.

6. CONCLUSIONS AND FUTHER WORK

The framework developed throughout this work and presented here is the first in a series of developments with the aim of improving and optimising manual lay-up. Both design for manufacture and in-process control are considered in order to realise both short and longer term benefits to composites production. The three main research and development activities of prediction, capture and feedback have all been used to instruct and begin the creation of a knowledgebase. This knowledgebase will be used as part of a wider double-loop learning cycle in order to give designers greater familiarity with the constraints and benefits of manual lay-up.

The predictive methods discussed in this paper can be used to determine the drape route and fibre orientation; estimate local forces and time to lay-up; and predict risk of defects. The outputs of these various predictive models still require analysis and approval by an expert in the subject, such as a highly experienced laminator or engineer familiar with the lay-up process. The predicted drape route is then used to make high-fidelity lay-up instructions, while the fibre orientation map is used for checking the local fibre orientation change due to shear. The productivity estimates and the defect risk can be used as metrics to be fed-back into the design process and iterated until an optimum design is found.

The touch-labour level interactions with the ply and tool can be captured and used to improve instruction sets when fed-back into the predictive cycle. The data can also be used to ensure conformance to instructions and for the training of new laminators. The capturing of quality information also has both process control and learning implications. Capturing snapshot data can be used to ensure the manufacture is proceeding according to specification. Data captured can be used in a longitudinal study to identify patterns in designs which have proven problematic.

The mechanisms for feeding this information back into the design process and making the data part of a knowledge system has scope for further development. The established framework gives some initial ideas for how this would function, but there are a number of external dependencies, such as organisational structures and cultures, which must be considered for it to be effective.

Further work remains in the development of all three activities. The predictive capacity still requires a high level of manual interaction and has likely geometric and material limitations. These limitations can be mitigated by capture and processing a wider array of parts and materials. The capture activity can be enhanced by identifying the tools used and the hand-level gestures and techniques discussed previously [23, 26]. The feedback and knowledgebase will require more longitudinal study and would benefit from industry buy-in.

7. ACKNOWLEDGEMENTS

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